IEA INTERNATIONAL ENERGY AGENCY

Transition from Uni-Directional to Bi-Directional Distribution Grids:

Management Summary of IEA Task 14 Subtask 2 – Recommendations based on Global Experience

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

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Abstract

This report summarizes the outcome of the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) Task 14 Subtask 2 activities with regard to high PV penetration in local distribution grids. The focus of this report is set on discussing technical PV integration issues in distribution grids – spanning high voltage, medium voltage and low voltage levels - of interconnected electric power systems and presenting solutions for the transition from uni- to bi-directional distribution grids. The recommendations are based on a case-study collection of best-practice examples provided by Subtask 2 participating countries.

The report is divided into three major sections. The section "**Transition from Uni- to Bi-Directional Distribution Grids**" discusses typical technical challenges from a system operator's perspective which will occur along the way towards PV as a major electricity source in national power systems. A simple three-stage model is used to allocate technical challenges for grid operators to different national PV penetration scenarios.

The section "**State-of-the-Art and Advanced Technologies for the Transition from Uni- to Bi-Directional Distribution Grids**" briefly introduces the technically most relevant solutions for an improved distribution grid integration of PV with respect to different PV penetration scenarios. Besides improved functionalities for smart PV inverters also novel assets for distribution system operators are discussed. Cost-benefit analyses highlight the significant economic potential of these solutions for reducing the overall costs of PV grid integration. Recommendations for a successful transition from uni- to bi-directional distribution grids are given based on the outcome of Subtask 2 and the experience of the Subtask 2 contributors in this field.

The final section discusses the **future prospects for the transition towards high national PV penetration scenarios**. Important elements, such as the necessity of aligning PV generation and demand, the provision of ancillary services by PV and the future interaction of smart girds, smart markets and smart inverters are discussed and current trends in research and development are highlighted.

Table of Contents

1 Introduction

As the share of solar electricity on the global electricity mix continues to grow, it becomes increasingly important to understand the technical and economic challenges associated with high PV penetration scenarios. Particular consideration needs to be given to understanding the specific advantages and disadvantages of high PV penetration; inverter based, weather dependent, decentralized - with respect to the reliability and stability of electric power systems. The long-term goal is to enable solar electricity to be fully integrated into power system operations - from serving local loads to providing ancillary services for interconnected transmission and distribution systems. There is a strong need for international R&D collaboration in order to collate and disseminate worldwide knowledge about high penetration levels of PV. The International Energy Agency (IEA) Task 14 is one international R&D collaboration dealing with increasing the share of PV energy in electricity grids.

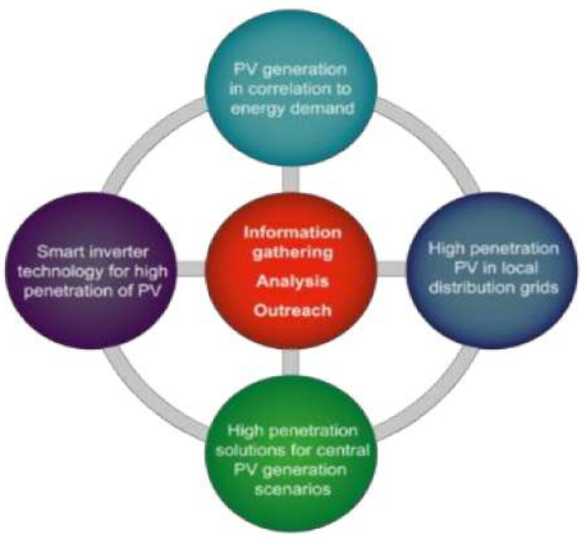

Figure 1: Organizational structure of IEA Task 14

The IEA is an autonomous organization which works to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA's four main areas of focus are: "energy security, economic development, environmental awareness, and engagement worldwide" [1]. The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R&D agreements established within the IEA and, since its establishment in 1993, the PVPS participants have been conducting a variety of joint projects in the application of photovoltaic conversion of solar energy into electricity. The main goal of

Task 14[1] is to promote the use of grid-connected PV as an important source of energy in electric power systems at the higher penetration. The aim of these efforts is to reduce technical barriers for achieving high penetration levels of distributed renewable systems. Figure 1 shows the organizational structure of the IEA Task 14.

During the past four years, national experts from 15 institutions[2] from around the world worked together within Task 14, Subtask 2 – High Penetration PV in Local Distribution Grids – in order to identify and share best practices for a technically and economically improved distribution grid integration of PV.

The current report summarizes the outcome of the IEA Task 14 activities with regards to high PV penetration in local distribution grids (high voltage, medium voltage and low voltage level) and gives an outlook on the requirements for national high PV penetration scenarios. In this context, the focus is set on interconnected power systems. Based on selected national high penetration PV case-studies (the case-studies can be found in the full report [2]), recommendations for a technically effective and economically efficient transition from uni-directional to bi-directional distribution grids are derived.

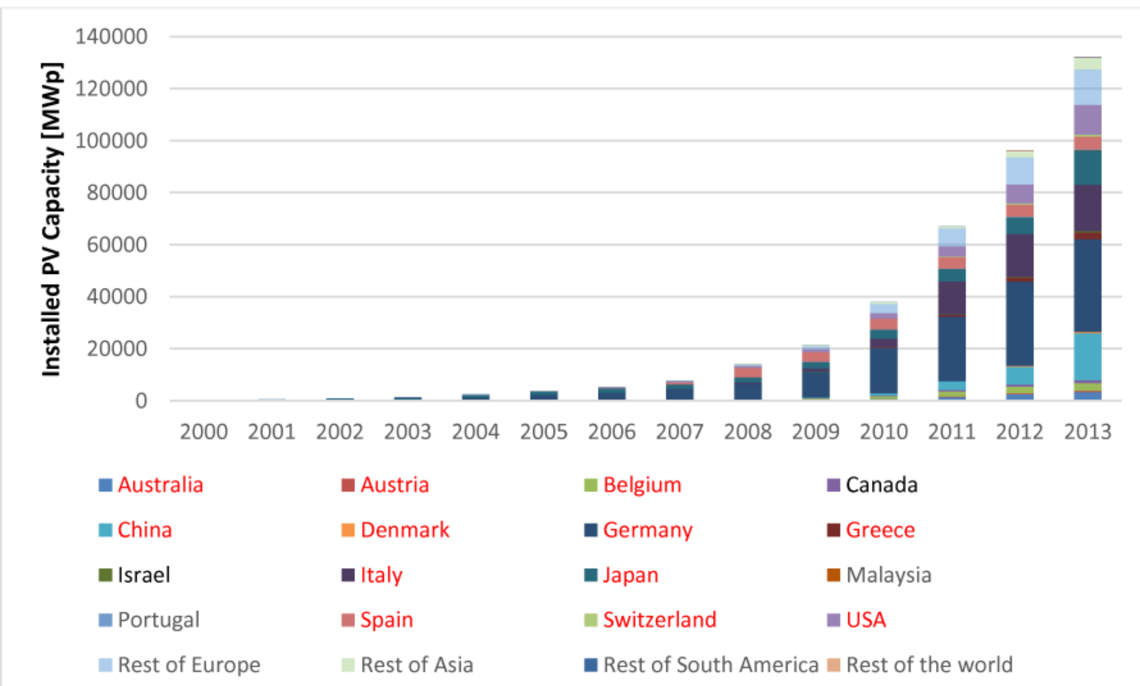

Figure 2: Evolution of the cumulative installed capacity in the task 14 participating countries and the rest of the world [MW], IEA PVPS/EPIA 2014. IEA Task 14 member countries, which provided best-practice case studies are highlighted in red.

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[1] http://www.iea-pvps.org/index.php?id=58#c92
[2] http://www.iea-pvps.org/index.php?id=62

In total, 132 GW of PV capacity was installed by the end of 2013, covering roughly 0.9% of the total electricity consumption (see Fig. 2). As of today, the IEA Task 14 member countries represent 85% of the worldwide installed PV capacity.

2 The Transition from Uni- to Bi-Directional Distribution Grids

The electricity supply system of every country will typically face three different development stages as it increases the share of PV to the total electricity mix:

Stage 1: Low/ medium PV penetration in a few distribution grids– Local consumption exceeds local generation (uni-directional distribution grids)
Stage 2: High PV penetration in a few distribution grids – Local generation exceeds local consumption (bi-directional distribution grids)
Stage 3: High PV penetration in many distribution grids – PV as a major electricity source

The technical and economic challenges that are associated with this transition process can be roughly distinguished between local and system (on a national scale) issues. Local challenges of high PV penetration scenarios effect distribution systems whereas systemic challenges will have an impact on the operation and stability of the national transmission system. Both perspectives have to be addressed by research, development and demonstrations in order to find solutions for a smooth transition from uni-directional to bi-directional distribution grids in the context of national high PV penetration scenarios.

Stage 1 (uni-directional distribution grids): This stage marks the beginning of the national PV deployment. A small number of distribution grids (i.e., distribution substation including downstream distribution system) experience a low level of PV penetration. This means that a small number of circuits, predominantly in rural areas, will show reverse power flows caused by PV generation in times of high solar irradiation. However, the distribution systems are still load-dominated, which means that no reverse power flows towards the upstream transmission system occur. The distribution system operator (DSO) will experience few voltage and loading issues associated with the increasing PV penetration and those issues observed are limited to the interconnected distribution feeder. On the transmission system level, no technical effects caused by PV power generation are generally observed.

Stage 2 (bi-directional distribution grids): At this stage, a small number of distribution grids with high local PV penetration occur. In contrast to stage 1, reverse power flows from

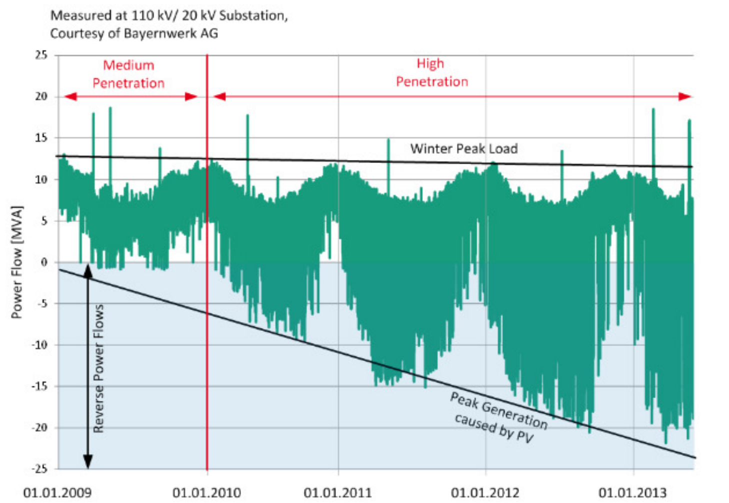


Figure 3: Example for the transition from consumption to supply grids (transition from stage 1 to stage 2) from the German IEA Task 14 case study. The power flow measurement data was recorded at a 110kV/ 20 kV distribution substation within the service area of the Bayernwerk AG. Courtesy of Bayernwerk AG, Germany.

the distribution system to the transmission system can be observed quite frequently. Within these highly PV penetrated distribution grids the installed PV capacity exceeds the local peak load many times over, leading to potentially very significant over-voltage and over-loading issues. Normally, grid augmentation becomes necessary in order to host the installed PV capacity properly. The increased (reverse) power flows and the restructuring of the grid lead to a changing reactive power behavior of the distribution system. In detail, this means increased reactive power consumption by conductors during times of high solar irradiation, due to increased active power flows, and increased reactive power generation by conductors at night, due to augmentation (e.g., additional cables). Often, these highly PV penetrated distribution grids will be identified as project regions to study the effects of high local PV penetration on the distribution system operation.

In parallel, the impact of bulk PV penetration on the transmission system operation can be observed for highly penetrated regions. This includes reverse power flows from distribution grids into the transmission grid which leads to an increased demand in re-dispatch of conventional power plants and revised procedures for congestion management.

Stage 3 (high national PV penetration): Stage 3 marks the final stage on the way towards PV as a major electricity source. The stage is achieved, if the overall power system is highly penetrated by PV systems. The focus of PV grid integration is now set on transmission system operation, including the provision of ancillary services from dispersed generation. Mature technical solutions for PV grid integration are required in order to cope with decreasing fault-currents on high and extra-high voltage levels as well as potentially severe frequency and voltage stability issues.

The three development stages are depicted by Fig. 4. Following the red path through these stages shows typical observations of distribution and transmission system operators for different PV penetration scenarios.

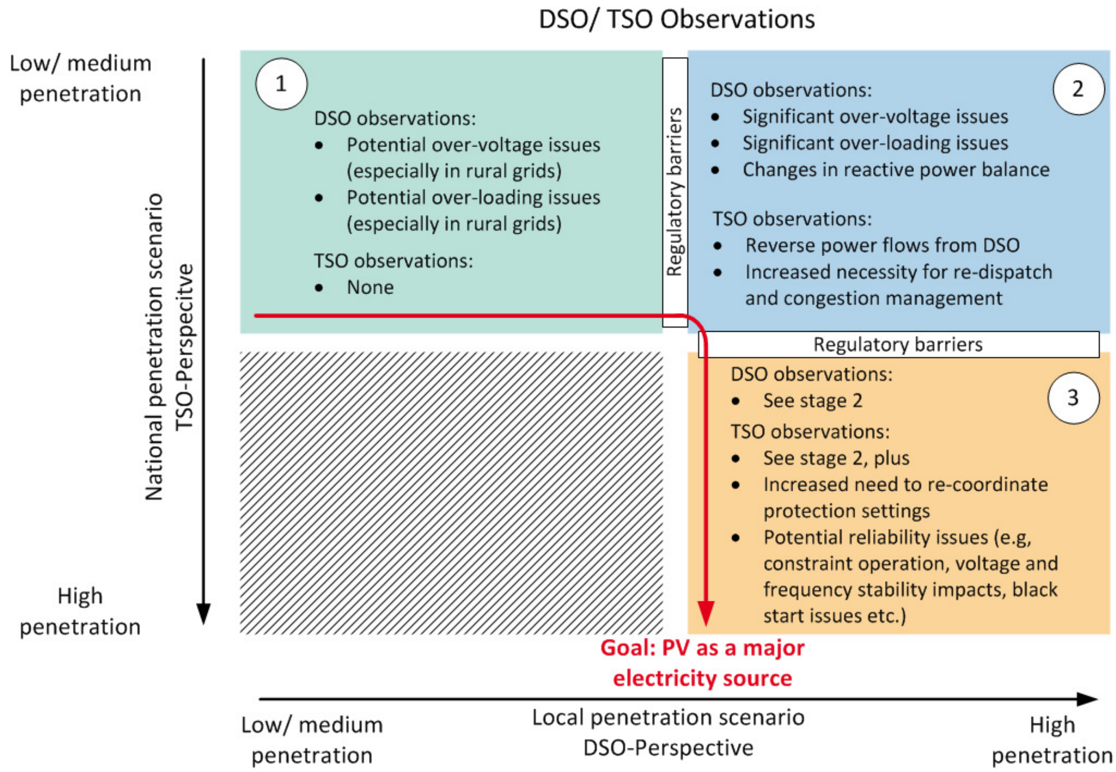


Figure 4: Definition of PV penetration stages and potential technical observations by distribution system operators (DSO) and transmission system operators (TSO)

Note: For a technically reliable and cost-effective transition from one stage to another it is extremely important to have the technology and the regulatory framework ready when effectively needed. This requires continuous adaption of network codes and laws in regards to high national PV penetration scenarios from an early stage on. Neglecting this process of early adaptation will most likely result in high grid integration costs as retrofitting of existing PV systems will become necessary (compare Section 3.4).

3 State-of-the-Art and advanced Technologies for the Transition from Uni- to Bi-Directional Distribution Grids

PV is as much part of the solution as it is part of the problem. Among other distributed energy resources (DER) technologies and the challenges that derive from their high penetration, PV has its share but it is not the sole cause. All the technical capabilities of different DER technologies have to be investigated aiming at proper grid integration, sustainable grid operation and customer participation.

To enable PV as a major electricity source and serve the energy plans of the future, the challenges summarized in Figure 4 will need to be overcome. PV technology should provide its own set of technical services and bear part of the responsibility among other renewable energy sources (RES) and non-RES technologies within an integrated environment and planning process. In the past, insufficient integration practices have led to inefficient economic and regulatory adaptations (e.g. retrofitting process in Germany due to the so-called 50.2 Hz issue) due to conservative forecasts on the expected PV evolution and the non-consideration of technical capabilities of PV systems to support system operation. Ideally and based on the experience that PV stakeholders and DSOs have gained so far, design and planning exercises should take these technical capabilities proactively into consideration.

Today, in different countries and depending on the local context (penetration level, the energy mix, the network characteristics and the regulatory framework) certain technical services are applied under different regulations (e.g. grid codes) in order to increase the hosting capacity of distribution grids for additional PV capacity. Those services are described below under those provided by the PV system (Chapter 3.1) and those provided by the operator (Chapter 3.2).

State-of-the-art services are described that encompass existing practices and techniques that are already successfully applied in one or more of the IEA Task 14 countries aiming at increasing the hosting capacity of distribution grids for additional PV capacity. Moreover, advanced services which are currently being tested in certain countries (normally in the context of a demonstration project) are introduced as well. However, most of the advanced services are not yet commercially available and often not in compliance with the current regulatory framework.

3.1 Technical Services offered by PV Systems

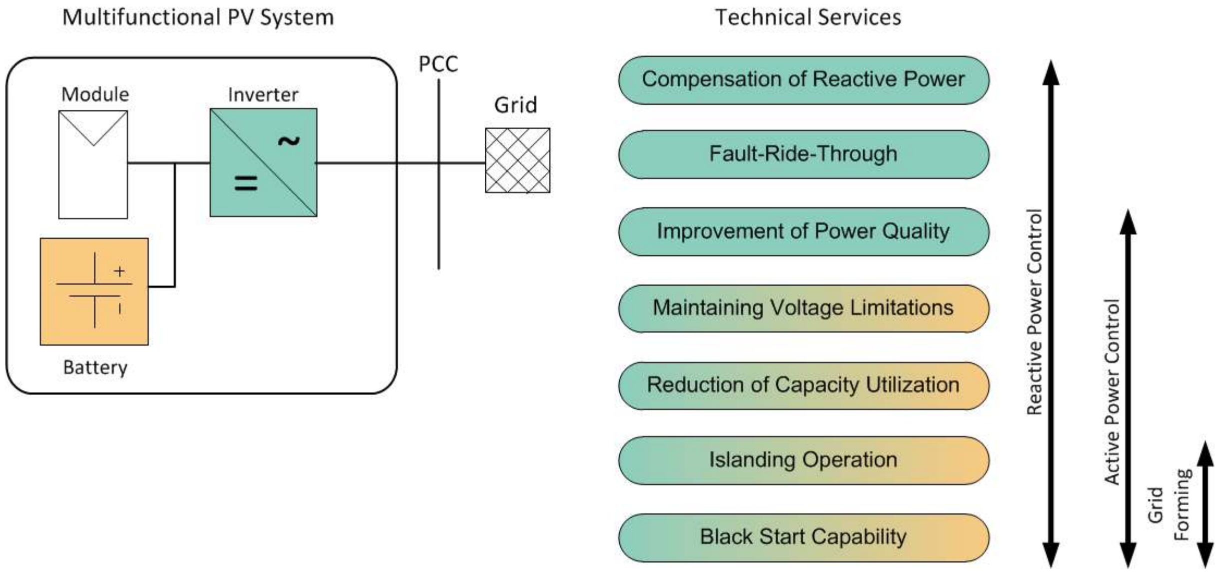


Figure 5: Technical services offered by multifunctional PV systems.

The services listed include the most promising techniques for increasing a grid's hosting capacity that can be either already provided by PV systems or that could be provided by PV systems in nearby future with some relatively easy software and hardware modifications of the inverter. Some of those technical services have already been introduced by the country's interconnection guidelines and their provision is considered mandatory, while some other services are mainly driven by incentives and the regulatory framework (e.g. self-consumption, storage). In most cases, it is the inverter (and sometimes an additional storage device) that enables PV systems to provide a broad range of technical services for grid operators (compare Fig. 5).

In the previous chapter, overcoming severe voltage issues was defined as one of the major DSO challenges for local high level PV penetration scenarios (refer Fig. 4). Because of this, the following summary focuses on those technical services (state-of-the-art and advanced) who can contribute to maintain voltage limitations in distribution grids.

3.1.1 Reactive Power Control

The provision of reactive power can be distinguished by static reactive power control and dynamic reactive power control. Static reactive power provision is used to maintain voltage limitations during normal grid operation (change or reactive power output in seconds to minutes), while dynamic reactive power provision is required to ride through sudden severe voltage drops (change of reactive power output within milliseconds).

Static Reactive Power Provision
The idea of using reactive power as a tool for maintaining voltage limitations at distribution system level derives from traditional power system operation, where reactive power control is often mandatory for large generators at high or extra high voltage levels in order to support the overall voltage stability in the grid. In contrast to the these vital services, the sole purpose of providing reactive power at lower distribution system levels (e.g. medium or low voltage level) is to cause additional reactive power flows over the local conductors and transformers to in turns lower local voltage raises caused by dispersed generation. The effectiveness of reactive power provision is based on the resistive R and reactive X shares on the local grid impedance (often expressed as X/R ratio). The higher the X/R ratio of the local impedance the higher the effect of reactive power on the voltage magnitude. However, lower voltage levels are often accompanied by low X/R rations, which hamper the technical effectiveness of reactive power provision on the local voltage magnitude. Nowadays, most of the state-of-the-art PV inverters are capable of providing static reactive power.
State-of-the-Art Capabilities: In many IEA Task 14 member countries, static reactive power provision capability is required by PV systems, but its practical utilization is up to the local DSO. Typical applications for residential scale PV systems focus on autonomous ways of providing reactive power (that is without additional information and communication interface to the DSO), such as the provision of a fixed power factor. Utility scale PV systems typically come with a remote control interface that allows DSO to transmit reactive power set values to the PV plant. A list of the IEA Task 14 member countries which are currently demanding some sort of static reactive power provision by PV inverters can be found in the Annex.
Advanced Capabilities: Voltage dependent reactive power provision (so-called volt/var control) is considered to be more advanced as it provides reactive power based on the locally measured voltage magnitude of the inverter. Various research projects are currently investigating the technical performance of such a control strategy with a strong focus on local stability issues [3], [4], [5]. It is expected that volt/var control will become an interesting option for providing reactive power for voltage support purposes in the nearby future due to its technical effectiveness (reactive power provision only if needed).

Dynamic Reactive Power Provision
Similar to the reactive power provision for static voltage control, PV systems and other generating units connected mostly to the medium and higher voltage levels are required in some countries to inject reactive current in order to stabilize the grid in cases of voltage collapses. This technical service is known as fault-ride through. Depending on the depth and duration of the voltage dip, the photovoltaic system is required to stay connected, inject reactive current or disconnect based on a characteristic that is part of each country's technical specification.

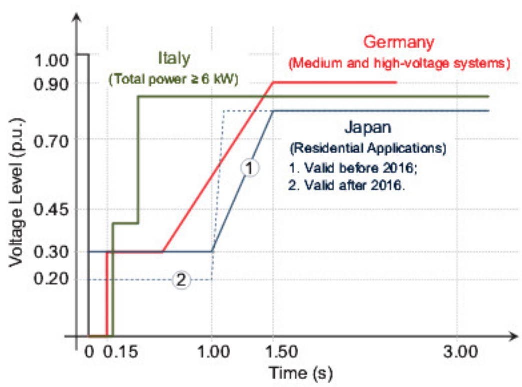


Figure 6: Low voltage ride-through requirements in different countries.

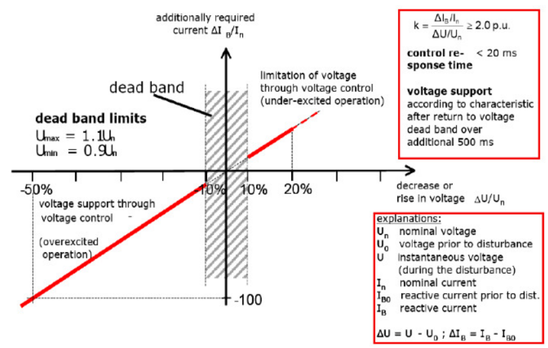


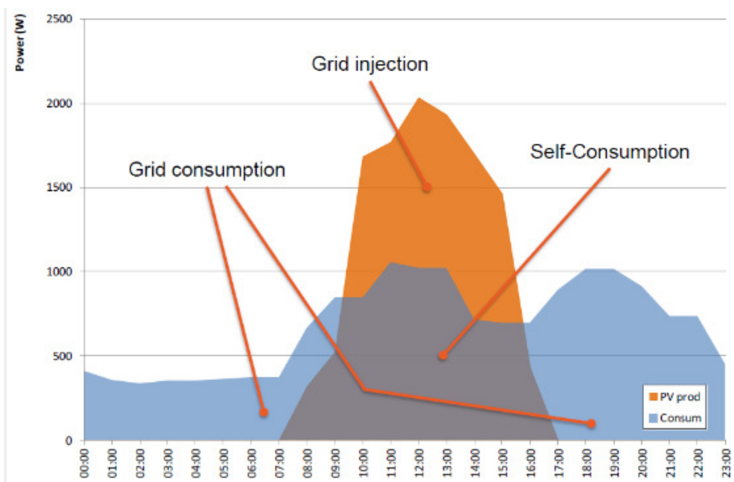
Figure 7: Method for reactive current provision for systems connected to the medium voltage in Germany (right) [6], [7]

State-of-the-Art Capabilities:
A list of the IEA Task 14 member countries which are currently demanding some sort of dynamic reactive power provision by PV inverters can be found in the Annex.

3.1.2 Active Power Control

The idea of controlling the active power output of PV systems to provide technical services to the DSO is gaining in importance. Typically, active power control – that is actually active power reduction – is a common tool for DSOs to overcome short-term network congestions by reducing the power output of utility scale PV systems. However, using the capability of PV inverters for fast active power reduction in the context of voltage control might be a technically promising service as well. Of course, reducing the active power output of PV systems has the negative side-effect of reducing the turnover for PV plant operators. Therefore, the additional application of storage systems (store surplus PV energy) and/or intelligent load management (increasing load in times of high PV feed-in) might become an economically reliable alternative to pure active power reduction.

Active Power Control by PV Inverters
The simplest form of active power control at the point of common coupling (PCC) is to solely use the PV inverter for active power reduction. Usually, the active PV power output reduction based on a reference signal, which is either the voltage at the connection point of a PV system or a set point remotely defined. In order to avoid voltage rises beyond the permitted voltage band or an overloading of grid components, PV inverters can autonomously or remotely adjust their active power output and hence contribute to the static voltage support or the congestion management, without shutting down completely. This type of service can be easily applied (mainly software modifications) for autonomous voltage control. For remote active control, a communication infrastructure between the PV plants and the system operator is needed.
State-of-the-Art Capabilities: Fixed active power curtailment: Fixed curtailment is a passive solution that caps the PV power output at a fixed value (can be a contracted value), normally a percentage of the nominal PV AC capacity or STC power. Fixed curtailment is applied at the point of common coupling (PCC) and is implemented during the connection of the system (inverter setting) or controlled by a meter or a specific device. This capability is placed in order to shave PV peaks and hence reduce the need for PV driven grid reinforcements. Depending on the national regulatory framework, generators can be compensated for any energy that is curtailed. In Germany for example, a fixed active power curtailment to 70% of their installed STC capacity is required for residential scale PV systems (up to 30 kWp) that do not have a remote control interface. Remote control interface: In many countries, remote control interfaces are mandatory for PV systems from a certain capacity upwards. As described above, the purpose of remotely controlling the active power output of PV systems is rather to ensure a reliable congestion management than to control the grid voltage. A list of the IEA Task 14 member countries which are currently demanding active power control capabilities for either voltage control and/ or congestion management purposes by PV inverters can be found in the Annex.
Advanced Capabilities: Some research projects are currently investigating the technical and economic potential of an autonomous and voltage dependent active power control (volt/watt-control) similar to the volt/var droop-characteristics [4], [5]. It is expected that volt/watt control can become a technically and economically reliable additional service that can be provided by PV inverters.

Increasing Self-Consumption and intelligent Load-Management
If PV power reduction is not the preferred solution, methods for increasing the PV self-consumption might be an option. By definition, self-consuming PV electricity reduces the power feed-in at the point of interconnection and hence can reduce the occurrence of voltage problems (i.e. self-consuming during peak PV output times). Additionally, self-consumption in combination with demand response techniques (i.e., intelligent load management) contributes towards the direction of optimizing the prosumers net demand profile by matching part of the demand with the electricity generation. It is first intended to decrease the reliance on direct support schemes but could, if properly designed, reduce PV impact on the power systems. This solution is less technical and more incentive-driven. The prosumers should willingly choose to self-consume when they see the direct or indirect economic benefit. The use of demand side management could increase the positive impact of such a measure by shavings PV peaks without actually curtailing PV production.  **Figure 8: PV production peak-shaving strategy at household level [8]**
State-of-the-Art Capabilities: Until April 2012, Germany subsidized solar self-consumption by guaranteeing a special feed-in tariff for each kWh of self-consumed PV energy. As of today, the sole benefit of PV self-consumption comes from reducing net load of private households and industries (compare Fig. 8), which in turns reduces electricity costs. A list of the IEA Task 14 member countries which are currently incentivizing PV self-consumption can be found in the Annex.

Storage Systems

Another way of increasing PV self-consumption is using additional storage for surplus PV energy. Storing the electricity produced by PV modules reduces the risk of potential voltage raises or component overloading (especially during peak PV output times). Furthermore, by using sophisticated energy management systems, the demand profile at the PCC could be smoothed out by levelling load and generation. Storage contributes to the operational flexibility of the PV system but the sizing and technology used depend strongly on the desired behavior (increase the self-consumption ratio, peak shaving, ramp rate control, generation scheduling, etc.). In contrast to DC-coupled storage systems, AC-coupled storage systems will come with an additional inverter that could be used as an additional source of reactive power.

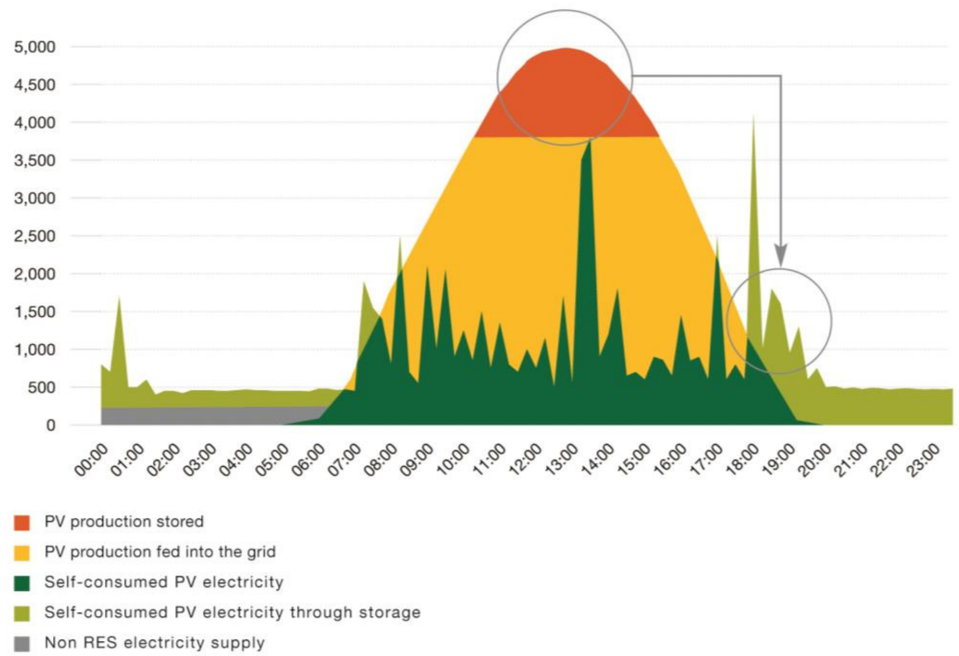


Figure 9: Peak shaving strategy using storage at household level. [9]

State-of-the-Art Capabilities:

A list of IEA Task 14 member countries in which prosumer storage for PV systems is currently being incentivized can be found in the Annex.

Advanced Capabilities:

Many research projects focus on the technical and economic aspects of using PV-storage systems for residential applications. Economic aspects of grid integration of PV-storage systems can be found in [10], for example.

3.2 Novel Assets for Distribution System Operators

In addition to the active and reactive power control capabilities of PV systems and PV storage systems themselves, distribution system operators nowadays are having access to novel operational equipment, such as MV/LV on-load tap changers (OLTC) or step voltage regulator (SVR) for example.

Note: All those controllable entities, PV as well as novel DSO assets, are referred to as smart grid technologies in the following.

In order to fully utilize the technical potential of these smart grid technologies, DSOs have to adapt their planning, coordination and operational strategies in order to increase the hosting capacity of their grids for connection of new DER. For grid operators it is therefore of importance to choose an appropriate set of control strategies from all available technical solutions. This usually requires a balance of rule of thumb screening techniques and sophisticated cost benefit analysis to assess and compare different planning and operational solutions including "smart grid technologies".

Grid operators' planning and operational solutions consist of conventional grid reinforcement techniques, which are used in most of the cases, and improved modern assets to increase operational flexibility. The latter requires additional or modified equipment and communication between network devices, power plants and network operators. The following list focuses on the most promising upcoming DSO assets, which can be used to increase the hosting capacity of distribution grids.

Control of HV/MV and MV/LV On-Load Tap Changer	Refers to "On-Load Tap Changer" (OLTC), meaning changing the transformer winding ratio by stepping up or down either the primary or the secondary windings and hence changing the transformer busbar voltage. OLTC operation strategies of substation transformers usually encompass autonomously and remotely controlled operation. State-of-the-art in the context of autonomous operations is to measure the secondary voltage and set the taps in order to maintain the voltage magnitude within the downstream distribution grid. In the context of remote control different operation modes exist. One common operation mode is the so-called wide-area-control (OLTC controls voltage of remotely measured nodes), for example.

Booster Transformer	This type of MV-MV and LV-LV transformer are used to stabilize the voltage along heavily loaded branch feeders. Usually, booster-transformers are used in long feeders with dispersed consumers to boost the voltage under heavy load conditions. Nowadays, it is also considered as a solution to control the voltage in feeders with high shares of PV. Therefore, the implementation of co-generation modes is required.

VAR-Control	Reactive power can be provided by fast-acting power electronic devices, such as Static VAR Compensators (SVC) for example. Its purpose is mitigating voltage raises and/ or compensating reactive power by injection of reactive currents. In contrast to reactive power provided by PV inverters, SVCs are a DSO asset.

Network Re-configuration	This can be considered as a part of conventional grid reinforcement measures. However, automatic concepts for feeder reconfiguration can be a beneficial future aspect of operational planning of distribution grids. Besides increasing the voltage and current related hosting capacity of distribution grids, reduction of network losses could be within the scope of automatic feeder reconfiguration.

Closed-Loop Operation	The purpose of closed-loop operation of distribution grids is to increase the short-circuit power of interconnection points within the grid. Higher short-circuit power increases the "strength" of the grid and hence reduces the effect of dispersed power feed-in on voltage magnitudes. Closed-loop operation is common practice at the HV level and above but it could affect existing protecting settings at MV and LV level.

Central Storages	This asset mainly refers to large scale static storage systems solutions that currently induce space requirements and high investment and operational costs. However, storage at DSO level could solve voltage and congestion issues and improve the flexibility of the distribution system. Typically, DSO storage provides peak shaving, load levelling, power quality services and of course it can be used as a back-up solution for frequency control services and black start operations.

3.3 Cost-Benefit Analyses

Choosing an appropriate technology from the above mentioned approaches is subject to the following influencing factors:

- Technical feasibility
- Regulatory framework
- Economic reliability

In order to assess the economic reliability, various cost-benefit analyses were performed in different research projects [5], [10], [11], [12], [13]. One example is based on the German case study as described in [2], [5]. The cost-benefit analysis compares different autonomously operating voltages control strategies, provided by PV inverters and MV/LV transformer with OLTC, for two real LV grids. The applied methodology is described in [3]. Figure 10 compares the resulting net present value of applying different voltage control strategies over a period of ten years with constant PV growth. The figure clearly shows that the application of voltage control strategies reduces the grid integration costs of PV compared to traditional grid reinforcement (no voltage control).

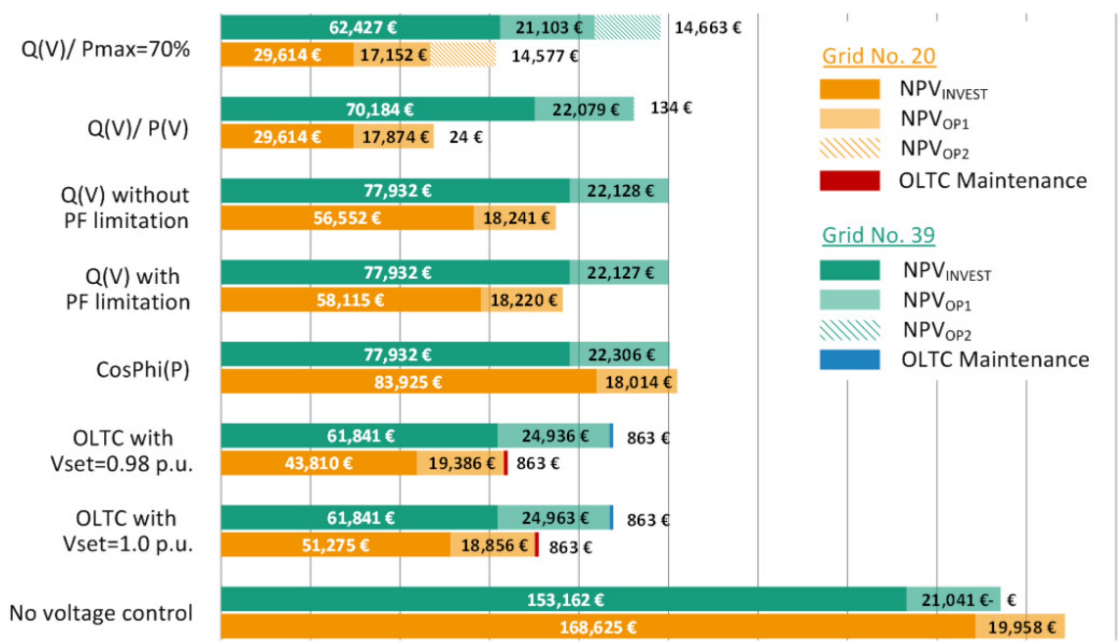


Figure 10: Total net present value (NPV) of investigated local voltage control strategies referred to the beginning of year t1. NPV_{Invest}: Grid reinforcement, NPV_{OP1}: Network losses + maintenance, NPV_{OP2}: Reduced PV feed-in. [5]

3.4 Recommendations for the Transition from Uni- to Bi-Directional Distribution Grids (from Stage 1 to Stage 2)

As described above, there is a wide range of solutions that can be applied either by the PV inverter or by the network operator (or combinations of both) in order to increase the hosting capacity of distribution grids for additional PV capacity.

Each of those measures has to be technically and economically assessed. There is no single optimum solution that can be applied in any case with the same impact on costs. But the tendency becomes clear: Using the active and reactive power control capabilities of state-of-the-art PV systems and novel DSO assets reduces the costs of PV distribution grid integration significantly. To utilize the technical and economic potential it is necessary to adapt long term grid planning principles accordingly. To increase acceptance and raise awareness for this kind of applications among DSOs, local regulatory authorities together with technical experts should be mobilized in order to establish a flexible framework which incentivizes the utilization of PV control capabilities and novel DSO assets.

Adaptation of the regulatory framework:

In some countries, DSOs cannot apply certain techniques due to regulations which guarantee full costs compensation only, if certain efficiency standards are met. State-of-the art and advanced smart grid technologies, such as reactive power provision by PV and/or OLTCs can contribute to lower PV grid integration costs considerably, but could also lead to slightly increased network losses. Revisions of these standards are necessary to fully utilize the technical and economic potential of smart grid technologies.

Figure 11 shows how the role of PV will change from local high penetration scenarios to national high penetration scenarios. With increasing PV penetration, PV itself needs to become an active part of power system operation.

Recommendations:

- If high national PV penetration scenarios are expected, it is important to get network codes and laws ready in time to pave the way for an active PV contribution on power system operation (preparation for stage 3):
  - Readiness of frequency support mechanisms provided by PV inverters (e.g., implementation of local P(f) droop characteristics)
  - PV systems should be equipped with remote control interfaces from an early penetration stage on. Otherwise, high costs for retrofitting existing PV systems might occur at a later stage.
- If the autonomous reactive power capabilities of smart PV inverters are to be used to increase the hosting capacity of distribution grids for additional PV capacity, the following advices should be taken into consideration:
  - High PV deployment can happen quickly. It is therefore important to make a decision about the usage of reactive power by PV at an early penetration stage. Otherwise, there is a significant risk of having many PV systems without reactive power capability connected to the grid.
  - There are many different variations available: DSOs should opt for control strategies that provide reactive power in a technically efficient manner (Q only if technically required). This means volt/var control rather than fixed reactive power provision or fixed power factors.
  - In order to reduce costs for grid reinforcement and/or grid augmentation, the reactive power capabilities of PV need to be considered already at grid planning stage.
- Temporal active power reduction can save grid reinforcement and/ grid augmentation. However, the application should be handled with care as it could have a significant impact on the PV owner’s return of invest.
- Novel DSO assets (OLTC, power electronic devices etc.) can help to increase the hosting capacity of distribution grids. However, they often come with lower efficiency ratings compared to mature technologies. In this context, it needs to be checked if current efficiency standards hamper an otherwise economically beneficial application of those assets.

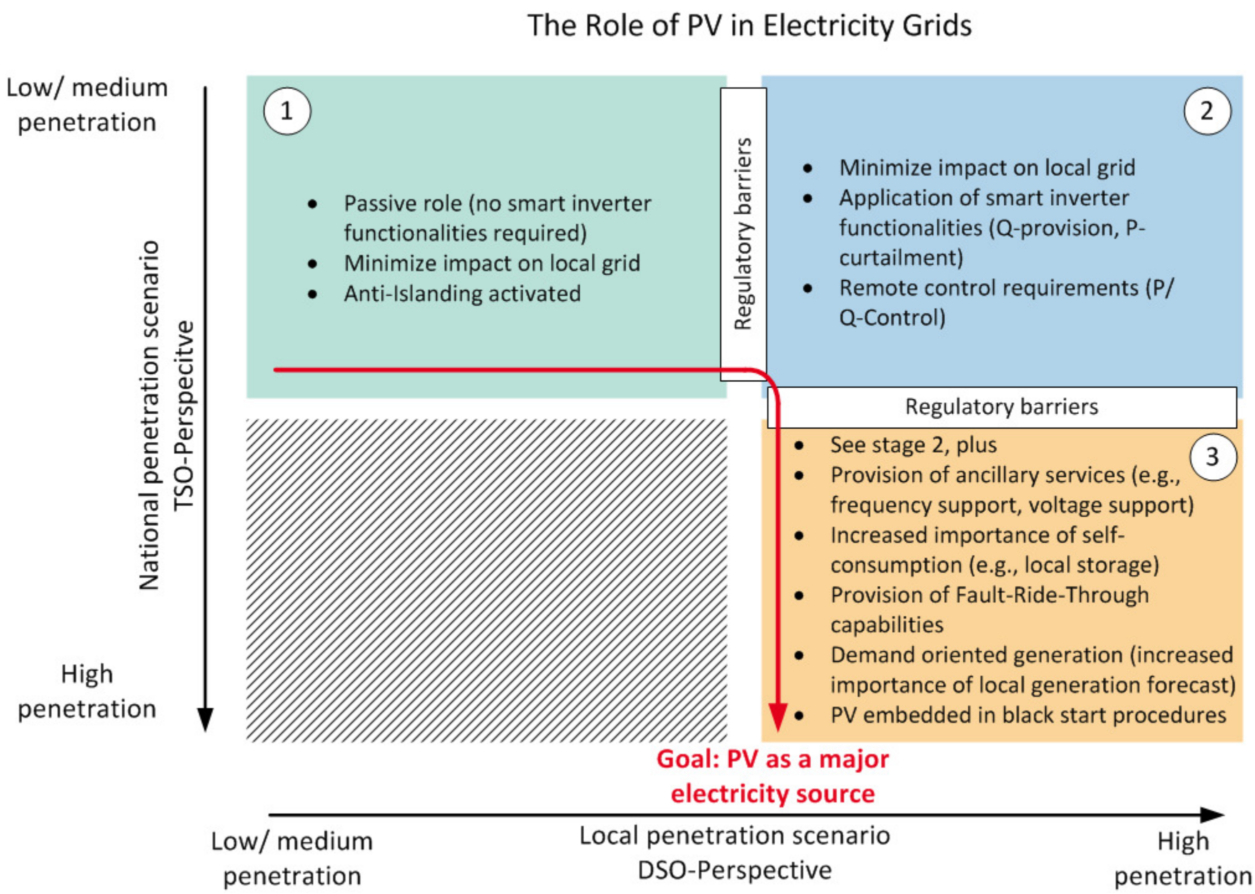


Figure 11: Requirements on the role of PV in electricity grid.

Regulatory Barriers

Often, the transition from one penetration stage to another becomes possible only by overcoming certain regulatory barriers, which hampered further PV deployment in the past. An example for still existing regulatory barriers are capacity limits, introduced by DSOs, which limit the installed capacity of PV on circuits or substations. Studies are currently being carried out questioning these limitations (compare Australian case-study "Carnarvon" in [2]).

4 Entering the Final Stage: Future Prospects for the Transition towards High National Penetration Scenarios

As of today, most of the IEA Task 14 countries have already entered stage 2, where high level PV penetration is a reality for a certain number of distribution grids. Significant reverse power flows can already be observed in several countries at transmission system level during times of high solar irradiation. At the same time, power feed-in from other renewable energy sources, such as wind or biomass, adds on top of PV generation and together forces conventional fossil-fueled generation to reduce their power output (compare Fig. 12). As more distribution systems are changing from consumption to supply grids, high national penetration scenarios arise (stage 3). As a consequence of an increasing share of generation capacity connected at the distribution level, new challenges for a stable operation of the overall power system have appeared. Traditional collaboration strategies between transmission and distribution systems operators and their role in the overall power system operation have to be reconsidered. This transition process will open new opportunities for existing or newly installed PV systems for actively participating in the power system operation and hence to prove their suitability as a major electricity source in future power systems. In this context, advanced PV control capabilities could become a tool for supporting DSOs in the transition from a passive to an active distribution system operation.

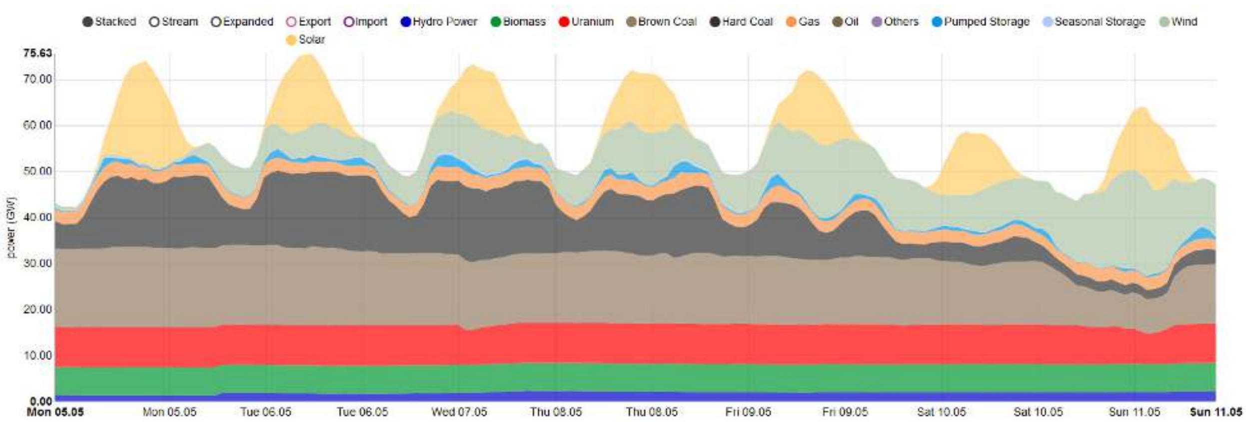


Fig. 12: Power provision in Germany in May 2014 [14]

Several intertwined elements – a decrease in electricity demand due to economic drivers, overcapacity, the emergence of low operational cost technologies such as PV and Wind, Emission Performance Standards and the increasing need for flexibility - have led to a decrease of power spot market prices and a reduction of full load hours, especially for coal (hard and brown coal) and gas-fired power plants. As a result, an increased number of conventional power plants are planned to be shut-down by their operators, due to financial reasons [15]. Among them, power plants which can be considered as system relevant in terms of generation adequacy or for the provision of ancillary services to the transmission system operators.

This tendency pushed energy regulators in some countries to think about complementary remuneration mechanism on the top of the classical energy only markets. Variants of the Capacity Remuneration Mechanism have already been implemented or are planned in different parts of the world. The increasing occurrence of reverse power flows coupled to a decrease of the prices and volumes at which conventional generators can trade their production on power markets lead to a change of paradigm for the operation of power systems.

It also illustrates that although significant PV capacities have been interconnected to power systems in some countries, they are still not sufficiently embedded into the overall power system operation to guarantee a secure and reliable grid operation under the absence of conventional power plants. While PV is becoming a mainstream source of electricity, further improvements on PV system integration is required. Achieving IEA's vision of PV meeting 16 % (almost 4 TW) of the global electricity demand by 2050 [16] will require fundamental changes in the way the electricity system is operated and how PV is integrated. The key challenges to achieve such a high level PV penetration scenario whilst guaranteeing a secure and reliable power system operation will be to **make PV generation more system-oriented while keeping the interest of and empowering customers and other market participants (smart market)** and to make use of the flexibilities of modern PV inverters and PV storage systems to **provide system relevant services (smart grid)** to DSOs and TSOs.

Additional information on power system operation planning with high PV penetration can be found the final report of Subtask 3:

K. Ogimoto, Y. Ueda, I. Kaizuka, K. Washihara (2014), „Power system operation planning with PV integration",". IEA-PVPS Task 14: High-Penetration of PV Systems in Electricity Grids. Subtask 3, Report in the context of the International Energy Agency PVPS program.

4.1 Aligning PV Generation and Electricity Demand

A key element for a more demand driven PV generation is to move from static feed-in-tariff systems, where pure active power feed-in is incentivized, towards more demand oriented systems. For achieving high level PV penetration scenarios novel, preferably market driven mechanisms are needed on a national as well as local level in order to align PV generation and electricity demand. These novel development policies should aim also at fulfilling the needs of power systems, dominated by variable and inverter based technologies.

- The first stage of demand oriented PV generation has to take place on a local level, where locally generated PV energy is used to cover domestic loads. In this context, storage systems or manageable loads controlled by sophisticated energy management systems can be used to ensure customer's interest by increasing the PV self-consumption (compare chapter 3).
- On a second stage, the same local energy management system can be integrated in a central management system to receive signals (prices or activation). The local energy management system will decide whether the locally generated PV energy shall be used to cover domestic loads or if the energy gains higher yields, if sold to the market or a system operator via a virtual power plant.
- Reliable local PV and load forecasting systems are essential to determine the available amount of energy on a day-ahead and intraday basis [17].

Key recommendations and technology gaps:

Move from static FIT systems to demand oriented development policies ensuring both:

- Customer needs by matching the local consumption (at the consumer or community level) with local generation.
- Systems needs by integrating local energy management systems in a central coordination.

4.2 Provision of Ancillary Services

The reduction of conventional fossil-fuelled generation capacity is a logical and intended consequence on the way towards decarbonized electric power systems relying mainly on renewable energy electricity. It also means that alternatives for providing ancillary services to TSO and ensuring the new DSOs needs have to be found. Basic ancillary services for the operation of power systems are [18]:

- Frequency control (Primary, secondary, tertiary and instantaneous control)
- Voltage support (static/ dynamic)
- Grid operation (congestion management, capacity scheduling, reserve capacity)
- Black start and system restoration

In general, **PV power plants are technically capable of providing a wide range of ancillary services** [19]. However, it often is **the current market/ incentive model and the passive role of PV** in the electrical power system that hampers utilizing the technical capabilities of smart inverters.

Frequency control: The reliable provision of primary, secondary and tertiary frequency control is vital for a secure and reliable operation of electrical power systems. As of today, frequency control is predominantly provided by flexible conventional power plants and large pump storage systems. In general, PV inverters can provide fast acting active power regulation for frequency control purposes. However, the challenge in a future power system with high shares of PV capacity will be to reliably provide negative as well as positive frequency control, taking into account the uncertainty of PV power feed-in generation. Especially a reliable provision of positive frequency control (i.e., increasing active power output on demand) will require the presence of dispatchable loads and an encompassing generation portfolios. An isolated consideration of different generation technologies will not be sufficient to meet the future demand in frequency control services. But a combination of different generation technologies, storage systems and dispatchable loads could fill the gap that is caused by the retirement of conventional power plants. However, utilizing the **technical potential of PV for the provision of frequency control requires a revision of existing regulatory constraints and a profound understanding of the necessary composition of load and generation portfolios.**

As of today, instantaneous frequency control is provided by the inertia of rotating mass of synchronous generators of conventional power plants. Smart PV inverters can theoretically emulate the inertia of rotating masses [20]. However, scalability of such advanced concepts is difficult. For example, island power systems in the MW range would require additional devices such as energy storages (e.g., battery storage or flywheels) for being operated safely. Further research, development and demonstrations are needed in order to validate the synthetic inertia concept.

Static Voltage Support: Autonomous reactive power provision by PV Inverters for local voltage support at their PCC can be considered as state-of-the-art in some countries (compare Section 3). By replacing conventional generators at transmission system level, alternative reactive power sources for voltage control at transmission system level need to be established. In this context**, the reactive power flexibility of smart inverters could play an important role for a coordinated voltage support at the DSO's point of interconnection to the upstream TSO** (including the so-called Q@Night-capabilities). The utilization of this flexibility requires the presence of widespread communication and information technology as well as advanced optimization algorithms, which realize a technically and economically optimized reactive power dispatch between controlled entities (e.g. dispersed generators, on-load tap changer, STATCOM, SVR, etc.).

Dynamic Voltage Support: As of today, PV inverters connected to medium and high voltage levels already have to provide fault-ride-through capabilities in many different countries (compare Annex). Additionally, medium voltage connected PV inverters are already required to provide post fault current and active power recovery capabilities in some countries. In high penetration scenarios with a majority of the installed PV capacity connected to low voltage levels, the technical effectiveness of fault-ride-through capabilities of smart inverters at those voltage levels have yet to be demonstrated. For post fault capabilities, the need and the possible interactions with protections schemes at the distribution level have to be further analyzed.

Grid operation: Conventional grid operation encompasses also measures for congestion management, such as market based re-dispatch and/or temporal active power curtailment and reactive power management. Up till now, some system operators have direct control access to utility scale PV power plants but lack of higher-level intelligence that automatically coordinates the active and reactive power dispatch to solve network congestions in a technically effective and economically efficient way.

Black start and system restoration: The role of PV in black start and system restoration processes needs to be redefined for high national PV penetration scenarios. This includes also to evaluate the technical capabilities of smart inverters to build and operate micro-grids until the overall power system can be reliably restored.

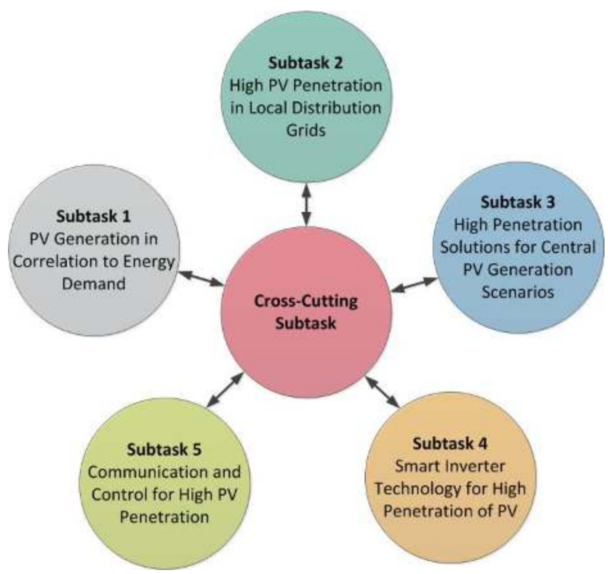
4.3 Interaction of Smart Grid, Smart Inverters and Smart Market

From the perspective of a PV system operator, fulfilling the requirements of smart markets and smart grids at the same time can sometimes be contradictorily. Hence, standardized procedures are required which regulate the responsibilities of smart grids and smart markets in future electric power systems. One basic step towards finding solutions is the BDEW Roadmap for the transition towards smart grids in Germany [21].

For the time being, a successful provision of most of the above mentioned ancillary services (smart grid) and market operations require a combination of reliable forecasting systems, standardized ICT backbones and higher-level intelligence, implemented and operated also at the distribution system level. Defining proper standards for technical solutions and role models (including business models) for the above mentioned issues will be a key factor for a successful transition towards secure and reliable high national PV penetration scenarios.

IEA PVPS Task 14 Future Activities

IEA Task 14 will continue its work on discussing future options and structures for the transition towards electric power systems with high-level PV penetration.



The work of Subtask 2 will focus on:

- **Activity 2.5**: Taxonomy of Distribution Feeders with high PV Penetration
- **Activity 2.6**: PV Interconnection Screening Techniques
- **Activity 2.7**: The Role of the DSO as a Service Provider to the TSO
- **Activity 2.8**: Improved Operational and Long-Term Planning considering high PV Penetration Scenarios

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